Artificial organisms that sleep

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Abstract Populations of artificial organisms live in an environment in which light is cyclically present (day) or absent (night). Since being active during night is non-adaptive (activity consumes energy which is not compensated by the food found at night) the organisms evolve a sleep/wake behavioral pattern of being active during daytime and sleeping during nighttime. When the population moves to a different environment that contains "caves", they have to get out of a cave although the dark conditions of the cave may tend to induce sleep. We study various solutions to these problems: evolving a light sensor, evolving a biological clock, evolving both a light sensor and a biological clock. The best solution appears to be evolving a light sensor that modulates a biological clock, a solution which may also be appropriate to solve other problems such as adapting to seasonal changes in daytime length.

1 Introduction

A population of organisms lives in an environment that contains randomly distributed food elements. The reproductive chances of each individual depend on the individual's ability to eat. The sensory receptors inform the individual about the location of the food elements and the individual responds to this information by approaching the food elements and eating them. Individuals that eat more are more likely to leave offspring than those that eat less. In fact, it is the selective reproductive rate that originally creates the ability to find food in these organisms. Notice that moving in the environment has a cost in terms of energy. For each movement an individual's energy is reduced by some amount. However, the energy acquired by eating a single food element is considerably greater than that consumed at each time step by moving around in the environment. Therefore, the organisms tend to move all the time.

Consider now a slightly different scenario. Everything is identical with the exception that periodically the light which illuminates the environment goes away. Cyclically, a number of time steps with light (day) are followed by a number of time steps with no light (night), and then light returns, and so on. When it is dark the organisms cannot see well so that they can make mistakes in identifying the location of food elements. As a consequence, it is uneconomical for them to move around in search of food at night in that the energy spent by moving around may not be compensated by the energy acquired by eating. For the organisms it would be adaptive to develop a somewhat more complex behavior: sleep (don't move and therefore don't consume energy) at night, and be active (move around looking for food) during daytime. The individuals that develop this more complex behavioral pattern, which includes not only a component of food finding ability but also a component of appropriate sleep/wake behavior, are more likely to reproduce than the individuals that perhaps are very good at finding food but don't sleep or stay awake appropriately.

What kind of organisms can develop this more complex behavior? How should the nervous system that controls their behavior be organized in order to make this more complex behavior possible? While the sleep/wake behavioral pattern is a classical research topic with real organisms [3][6], little work has been done on artificial organisms or using simulations. (For neural network models of possible functions of sleep, see [4][10]. For non-agent-based mathematical models of sleep regulation, cf. [1][2]). In this paper we study the evolutionary emergence of the sleep/wake pattern by describing various simulations in which we manipulate the nervous system that controls the behavior of the organisms and explore the consequences of possessing different types of nervous systems. (For a general description of the approach, cf. [8].) In Section 2 we describe what is common to all the simulations. In Section 3 we describe what makes the various simulations different and the results of the simulations. In Section 4 we discuss the results.

2 Night and Day

The environment is a square of 15x15=225 cells. Each individual organism lives alone in its own copy of the environment. At any given time the environment contains 3 food elements, randomly distributed. When the organism happens to step on a food element, it eats the food element and a new food element appears in a randomly selected position. Each food element contains 30 energy units. One unit of energy is consumed at each time step when the organism is moving while no energy is consumed when the organism is not moving (it sleeps).

The entire lifetime for all individuals lasts 9 days. One day is 24 hours of 60 minutes each, where 1 minute corresponds to a single input/output cycle of the organism's neural network. Hence an individual lives a total of 12960 minutes. One day includes 12 hours of light (daytime) and 12 hours of dark (night). Both light and dark do not appear suddenly but they set in gradually.

In all simulations the organisms' behavior is controlled by a core neural network with two sensory input units encoding the position of the nearest food element, three hidden units, and two motor output units encoding the organism's movements (Fig. 1a). Among the output options there is a "do nothing" option, and when this option is chosen the organism does not move and we say that it "sleeps". When the other output options are chosen the organism is "awake" and it turns or moves around in the environment searching for food.

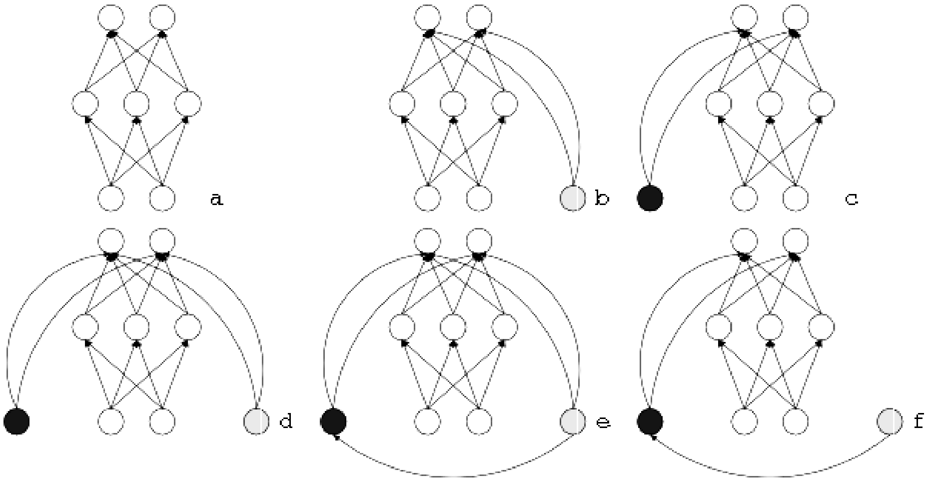


Fig. 1. Core neural network common to all organisms (a). Network with light sensor (b). Network with biological clock (c). Network with both light sensor and biological which independently influence behavior (d). Network with light sensor both independently influencing the organism's behavior and modulating the biological clock (e). Network with light sensor modulating the biological clock (f). (The network architectures were chosen to be as simple as possible.)

The activation level of the 2 input units encodes the location of the nearest food according to the following schema:

Food element exactly in front of the organism = 1;1
Food element exactly to the left of the organism = 1;0
Food element exactly to the right of the organism = 0;1
Food element somewhere in the front left quadrant = 1; 0,5
Food element somewhere in the front right quadrant = 0,5;1
Food element in the back of the organism = 0;0

The reliability of the organism's perceptual system depends on the light conditions of the environment. With probability = 1- L, where L is how much light is currently present in the environment, the correct input is replaced by a randomly selected input.
The 2 output units encode the organism's response in the following way:

1;1 = go one cell forward
1;0 = turn 90° to the left
0;1 = turn 90° to the right
0;0 = don't move (sleep).

The initial population is made up of 200 individuals whose neural network's weights are randomly selected in the range between –2 and +2. At the beginning of its life, each individual is positioned in a randomly selected location in the environment and at the end of life the individual is assigned a fitness value which increases with the number of food elements eaten and decreases with the number of time steps in which the individual has been active, i.e., in which its output has been different from 00. The fitness formula is the following:

F = (30 x number of food elements eaten – number of active time steps)

The 20 individuals with highest fitness are selected for reproduction. They generate 10 offspring each and the new 20x10=200 individuals constitute the second generation (reproduction is asexual). An offspring inherits the same connection weights of its parent except that each weight has 25% probability to have its value changed by adding or subtracting a quantity randomly selected between –1 and +1 to the current weight value. (This high mutation rate has been chosen to avoid convergence on sub-optimal behavior of always sleeping.)

The population lives for 1000 generations in the environment we have described which contains only the food elements. Then, for the next 1000 generations, i.e., from generation 1001 to generation 2000, the population moves to a different environment in which 85 out of the total 225 cells are “caves”. In a “cave” it is deep dark and therefore when an individual enters a cave it perceives the food elements very badly. Caves represent a problem for our organisms. If the organisms have developed a behavioral pattern according to which they are active when there is light and they sleep when it is dark, they may simply go to sleep when entering a cave and never awake again since light never returns in a cave. How can they solve this problem?

We describe the main results of our simulations (20 replications for each simulation) using two measures: (a) total quantity of energy (= fitness), (b) total amount of time spent sleeping vs. being awake.

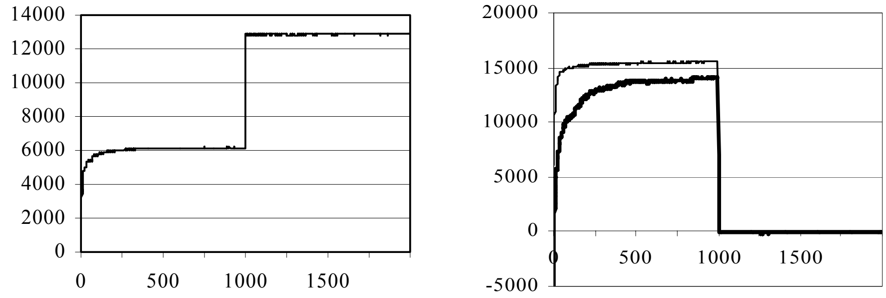
3 Simulations

3.1 Light Sensor

If an organism has absolutely no way to know when there is light in the environment (day) and when it is dark (night), it cannot behave differently during daytime and during nighttime. The best strategy in these circumstances is to be always active looking for food but this strategy is less than optimal given that being active at night consumes energy which is not compensated by the food found. However, if the organisms are informed by their senses about the light conditions of the environment, they can exploit this information by developing a better adaptive pattern: they can be active during the day and sleep at night. In the first simulation the organisms’ neural network includes an additional input unit (light sensor) which is directly connected with the motor output units (Fig. 1b). The activation function of this unit is 1- L (light). Therefore the unit reaches its maximum activation value at midnight (deep dark).

The population develops the desired more complex behavior in few generations and in all 20 runs of the simulation. The organisms tend to sleep half of their life, i.e., a total of around 6000 cycles (Fig. 2a), they sleep at night and are awake during daytime, and they tend to sleep in a single long sleep episode with perhaps 6-7 short sleep episodes both at dusk and at dawn, that is, just before and after the nightly long sleep episode. Their energy at the end of the first 1000 generations is quite high: it is around

15500 energy units for the best individual and around 14000 units for the average individual (Fig. 2b).



a b

Fig. 2. Organisms with light sensor. Total sleeping time for average individuals (a) and total fitness (energy) for the best (thin line) and average (thick line) individuals (b). Generations 1-1000: environment without caves (average of 20 replications). Generations 1001-2000: environment with caves (average of 15 replications).

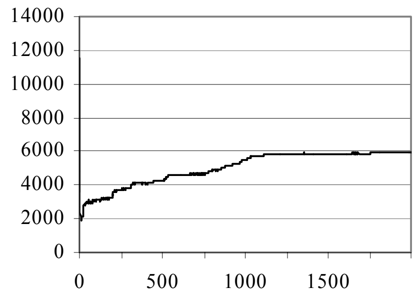
The possession of a light sensor provides a very efficient solution for the problem of sleeping at night in the environment in which the population lives for the first 1000 generations, an environment in which there are no caves and therefore "dark" univocally means "night". However, when the population moves to the environment with caves in which "dark" does not univocally means "night", the population tends to crash. In the new environment the information provided by the light sensor becomes ambiguous. "Dark" can mean "night", and in these circumstances the organism should respond by sleeping. But it can also mean "cave", and in these circumstances the organism should respond not by sleeping but by getting out of the cave. Hence, if the organism's sleep-wake behavior relies uniquely on the light sensor, the organisms will be disadapted to the new environment. In fact, in 15 out of 20 replications of the simulation, when an organism enters a cave it falls asleep and it never wakes up again since light never returns in a cave. The organisms sleep all the time and their energy goes to zero. In only 5 out of 20 replications (not included in the data of Fig. 2: Generations 1001-2000) the population shows some re-adaptation to the new environment. In these replications the organisms evolve new connection weights that allow them not to rely only on the light sensor in deciding whether to sleep or be active (consider that their motor output depends also on the changing input encoding food location) so that when they enter a cave they may occasionally respond by moving ahead and leaving the cave. However, their sleeping behavior is seriously disturbed (they have an average of 200 sleep episodes in a day) since with this re-adaptation they may happen to sleep even during daytime.

At any rate, given most initial conditions (replications of the simulation), the population with the light sensor simply would become extinct in the new environment. How can the problem be solved? How can organisms sleep during the night and be active during daytime if sensory information about the light conditions of the environment is ambiguous, sometimes meaning "night" and sometimes "cave" - which require two different responses. One solution is to develop a biological clock.

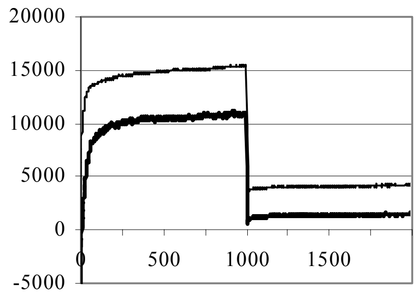
3.2 Biological Clock

In this second simulation there is no light sensor but the organisms evolve a biological clock that controls their sleep-wake behavior. The biological clock determines the activation level of an internal unit (biological clock unit) which is directly connected with the motor output units (Fig. 1c). The genetic information contained in the unit (i.e., in the nucleus of the neuron which is simulated by the unit) imposes a cyclical activation level to the unit [5][7][9]. The cyclical activation depends on two parameters which are encoded in an individual's inherited genotype together with the connection weights of the individual's neural network: the total length of the clock's cycle and the cycle's time of onset, that is, its synchronization with the day/night cycle. The best adapted individuals will have a biological clock's cycle of 24 hours and the cycle will be synchronized with the day/night cycle.

Evolving a biological clock that can appropriately regulate the sleep-wake behavioral pattern requires that two different things evolve at the same time: (1) the parameters of the biological clock, and (2) the synaptic weights of the connections linking the biological clock unit to the motor output units. In the simulation with the light sensor evolution's only task was to evolve the appropriate connection weights linking the light sensor unit to the motor output units since the activation level of the light sensor unit itself was determined by the external physical environment and it did not originate from inside the organism's body. In this new simulation, the activation level of the biological clock unit is determined internally and evolution has to take care of both aspects of the biological clock mechanism. Hence, its task is more complex. The results for the simulation with the biological clock are shown in Fig. 3.



a



b

Fig. 3. Organisms with biological clock. Total sleeping time for average individuals (a) and total fitness (energy) for the best (thin line) and average (thick line) individuals (b). Generations 1-1000: environment without caves (average of 18 out of 20 successful replications). Generations 1001-2000: environment with caves (average of 18 out of 18 successful replications).

For the first 1000 generations, when the organisms live in the environment with no caves, the results are similar to those of the simulation with the light sensor except that (1) the population with the biological clock evolves more slowly (this is clear with respect to total sleeping time but is also true of fitness), and (2) the average fitness remains somewhat lower (11000 energy units vs. 14000). Furthermore, while the simulation with the light sensor was successful for the first 1000 generations in all 20 replications, the simulation with the biological clock succeeds in only 18 out of 20 replications. All these differences appear to be due to the fact that for the reasons discussed above the biological clock mechanism is more complex to evolve than the light sensor.

However, what we are interested in are the results of the second part of the simulation, from generation 1001 to generation 2000. In all 18 successful replications of the simulation, the organisms with the biological clock are still able to acquire enough energy when they move to the environment with caves. In fact, their sleep/wake pattern is not affected at all: even in the environment with caves the organisms sleep only half of their time and they sleep at night. Their total energy is lower than in the environment without caves but this is because the environment containing the caves is an intrinsically more difficult environment, independent of the sleep-wake behavior of the organisms. In the environment with caves 85 of the 225 total cells of the environment, the “cave” cells, are always dark, which means that when an individual enters one of these cells food cannot be seen well even during daytime. Hence, the environment with caves has a lower “carrying capacity” than the environment with no caves. This is reflected in the lower energy of the population when it moves to the environment with caves.

The possession of a biological clock has the important consequence that the organisms have no special problems and can remain adapted when they move to the new environment containing the caves. The organisms of the simulation with the light sensor fell permanently asleep when they entered a cave since for them “night” and “cave” were the same thing: no perceived light. The new organisms “know”, because their biological clock tells them, when it is night and when it is day, and they have this information both when they are in the open environment and when they are in a cave. Since they do not depend on sensory access to light conditions for their knowledge of night and day, if the parameters of their biological clock are appropriately chosen they sleep when it is night and they are active when it is daytime independent of whether they are in the open environment or in a cave. Furthermore, their sleeping behavior does not appear to be disturbed as it was in those few replications of the simulation with the light sensor in which there was some re-adaptation to the new environment.

3.3 Both Biological Clock and Light Sensor

A third possibility is to have a neural network with both a light sensor and the biological clock. We have explored three different arrangements: (1) the light sensor and the biological both independently have an influence on the organism's behavior (the light sensor unit and the biological clock unit are directly connected with the motor output units: Fig. 1d); (2) the light sensor and the biological clock directly influence the organism's behavior but the light sensor also modulates the biological clock (the light sensor unit is connected with both the motor output units and the biological clock unit: Fig. 1e); (3) the light sensor has the only role to modulate the biological clock (Fig. 1f).

The results indicate that solution (1) gives the worst results from all points of view. It may be useful to have both a light sensor and a biological clock but the two mechanisms for regulating sleep should not function independently from each other but they should interact and be coordinated together within the brain. This is what happens in solutions (2) and (3), where the activation level of the biological clock unit depends both on the biological clock (an internally generated input) and on the activation level of the light sensor (an input from the external environment). Solution (2), where the light sensor both directly influences behavior and modulates the biological clock, gives the best results in terms of fitness but it is very difficult to evolve because of its complexity so that in almost half of the replications of the simulation the population crashes.

Solution (3), where the light sensor has the only task to modulate the biological clock, seems to give the best overall results (Fig. 4).

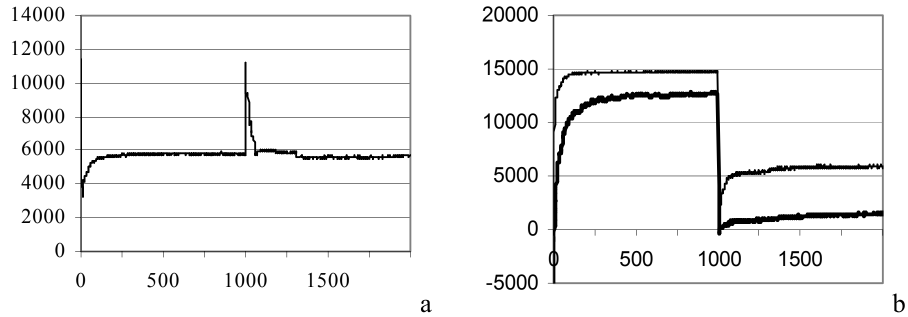


Fig. 4. Organisms with light sensor which modulates the biological clock. Total sleeping time for average individuals (a) and total fitness (energy) for the best (thin line) and average (thick line) individuals (b). Generations 1-1000: environment without caves (average of 20 replications). Generations 1001-2000: environment with caves (average of 20 replications).

First, all the 20 replications of the simulation succeed both in the first 1000 generations (environment without caves) and in the subsequent 1000 generations (environment with caves). Second, the neural network in which the light sensor modulates the biological clock has the advantage, with respect to the neural network with the biological clock but no light sensor, that the appropriate sleep/wake behavioral pattern evolves earlier, and the advantage, with respect to the neural network with the light sensor but no biological clock, that the correct sleep/wake behavioral pattern is maintained in the environment with caves (after a few generations of re-adaptation), at least in terms of total sleeping time, although the number of daily sleep episodes is greater than in the condition with only the biological clock. Finally, the neural network of Solution (3) reaches the highest fitness, at least for the best individual, in the environment with caves.

4 Discussion

If for a population of organisms it is adaptive to be active and look for food during daytime and to sleep at night the population is able to evolve the appropriate sleep/wake behavioral pattern provided that the organisms either directly sense the light conditions of the environment or can evolve an internal biological clock that tells them when to be active and when to sleep. In our evolutionary scenario the reason why it is adaptive to sleep at night is that when it is dark food cannot be seen well and therefore the little food which can be found does not compensate for the energy spent by being active at night. Future work might involve using our simulation scenario to investigate other possible reasons why it is adaptive to sleep. For example, one might need to sleep in order to eliminate dangerous substances accumulated when one is awake [3][6] or one might need to sleep in order to consolidate learning [4][10].

We have explored two different mechanisms that may underlie an organism's sleep/wake behavioral pattern: a light sensor and a biological clock. The light sensor is easier to evolve because the population has only to evolve the appropriate neural connection weights for utilizing the information directly provided by the senses concerning the light conditions of the environment. However, the information provided by the light sensor becomes misleading if it is possible for the organism to enter a local environment where it is dark during daytime, e.g., a cave. In these circumstances the organism would fall for ever asleep since light never returns in a cave.

Compared to the light sensor the biological clock is a more complex mechanism to evolve. The organism's body must evolve a cyclical mechanism, the clock, with the appropriate cycle length (24 hours) and the appropriate synchronization with the light/dark environmental cycle, and it must evolve the appropriate neural structure (connection weights) for utilizing the biological clock to generate the sleep/wake behavioral pattern. The advantage of the biological clock is that an organism won't fall asleep when entering a cave during daytime because its biological clock tells the organism not to do so.

Organisms can have both a light sensor and the biological clock. (In the real brain the light sensor may correspond to information in the retina directly reaching the neurons of the suprachiasmatic nuclei in the anterior hypotalamus, a subcortical structure. These neurons, influenced by the biological clock and by this input, trigger the pineal gland to produce melatonin that causes the brain to become asleep [5][7][9]) This double mechanism may not only produce better results than each mechanism working alone, as indicated by our simulations, but it might solve other adaptive problems not considered in our simulations. For example, we have assumed an environment in which the length of daytime and nighttime is always the same. This might apply tropical environments but it becomes progressively less true for environments at higher or lower latitudes. In the more northern regions of the Earth, for example, nights are shorter and days longer during the winter and the opposite is true in the summer. Humans tend to respond to these seasonal changes by sleeping more during the winter and less during the summer. The biological clock is an evolved mechanism and by itself it may not be able to keep trace of these relatively short-term environmental changes. The possession of a light sensor, in addition to the biological clock, might solve the problem. If the sleep/wake behavior of the organism uses information from both the biological clock units and from the light sensor unit, the information provided by the light sensor concerning the current light conditions of the environment can modulate the action of the biological clock and induce the observed seasonal changes in the sleep/wake behavior, re-synchronizing this behavior with the seasonally changing environmental conditions [3][6]. This might be another direction of future research.

Simulations of sleep/wake behavior using neural networks that live in and interact with an environment are interesting because they demonstrate an interesting aspect of the complexity of behavior of real organisms. In our organisms the reproductive chances of an individual depend on a complex interaction between the individual's ability to approach food and its sleep/wake behavioral pattern. The two "abilities" are not simply additive. An individual of course must be able to approach a food element efficiently when the food element is perfectly perceived in full daytime and it must also be able to sleep at night and be awake during the day. But if the environment becomes dark during daytime, e.g., when the organism enters a cave, the organism must respond to the input by getting out of the cave and in order to do so it must *both* avoid to fall asleep *and* ignore food.

Another interesting aspect of our simulations is that they make it clear that while organisms are not responsible for the inputs that arrive from the external environment to their neural network and they must only possess (evolve) an ability to respond appropriately to these inputs, the situation is different for the inputs that arrive to an organism's neural network from inside the organism's own body. The organism is responsible for these inputs. It must possess (evolve) not only an ability to respond appropriately to the inputs originating within its own body but also an ability to generate the appropriate inputs inside its body. In our simulations the biological clock mechanism includes both an ability to generate the appropriate inputs for the biological clock unit and the appropriate synaptic weights for the connections linking this unit to the motor output units. Evolution must evolve both aspects - one neural, the other one non-neural - of the biological clock.

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